DIFFICULTIES IN DETERMINING THE CAUSE OF REAL-WORLD CRASH INJURIES: A CASE STUDY OF A NASS INVESTIGATION

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ABSTRACT

This paper describes a National Automotive Sampling System (NASS) case in which a parked 1958 Chevrolet Bel Air was rear-ended by a 1991 Dodge Grand Caravan whose unbelted driver sustained fatal chest injuries despite the presence of an airbag. This particular case was chosen because different reviewers of the information from the crash investigation have proposed conflicting conclusions about the role of the airbag in the fatal injuries. The NASS investigators and others concluded that the driver bottomed out the airbag resulting in fatal chest injuries. Insurance Institute for Highway Safety researchers concluded that the driver either was out of position due to late firing of the airbag or was slumped over the wheel due to a high blood alcohol concentration; in either case they attributed the fatal injuries to airbag inflation forces. Thus, in one scenario the airbag had insufficient power, and in the others it had too much power.

Injury measures from a Hybrid III driver dummy seated in a Grand Caravan in a test re-creation of the real-world crash indicated low risk of serious injury to all body regions except the chest. The recorded chest compression was slightly higher than the injury reference value for a localized loading, but this measurement underestimated actual chest deflection because a postcrash inspection showed that off-axis loading had permanently deformed the ribs. During the crash test the airbag did not deploy late, but contact between the chest and steering wheel occurred because the steering column rotated upward. Separately, two static airbag deployment tests were conducted to determine the likelihood that the airbag could have caused the fatal chest injuries if the driver had been slumped over the wheel. Injury measures from these tests indicated a significant injury risk when the dummy was positioned close to the airbag module. The test results refute the hypothesis that the driver bottomed out the airbag; instead, either steering column movement or direct contact with the deploying airbag are the most likely cause of the fatal injuries.

INTRODUCTION

The knowledge, which began to accumulate in the 1990s, that inflating airbags can be responsible for the deaths of front-seat occupants has led to a continuing debate about the appropriateness of some of the federally mandated test requirements for airbag systems. Of particular concern is the extent to which airbag deployment forces can be reduced to lower the risks to out-of-position occupants while still preserving the life-saving benefits of airbags in serious frontal crashes. The real-world crash experience of airbag-equipped vehicles plays a central role in this debate.

The National Highway Traffic Safety Administration (NHTSA, 2001) has clearly identified cases in which airbag inflation forces have caused deaths and serious injuries in relatively low-speed crashes. Identifying airbags as the injury sources in such crashes is relatively straightforward because there is little damage to the vehicles and no realistic explanation for the injuries other than airbag inflation forces. What is not so clear, however, is the role of the airbag in a number of fatal frontal crashes at higher severities. Of particular interest are crashes in which there was no significant occupant compartment intrusion or occupant ejection and where airbags might have been expected to provide protection but did not because the occupants sustained fatal injuries.

A key question in many such cases is whether the fatal injuries occurred because the airbags had insufficient protective capability—i.e., the occupants bottomed out the airbags and, as a result, sustained fatal injuries from hard contacts—or because the occupants were out of position when the airbags first began to inflate and the inflation forces caused the fatal injuries. These two competing hypotheses lead to completely different conclusions concerning the appropriate force levels for airbag inflation. Airbag inflation force levels are too low under one scenario and too high under the other.

The Insurance Institute for Highway Safety (IIHS) has reviewed the frontal crashes of airbag-equipped cars that have been investigated as part of the National Automotive Sampling System (NASS) and, using the detailed NASS material—photographs, detailed injury data, etc.—summarized the likely causes of the fatal injuries (Zuby et al., 2001). Although in many cases the information available from the NASS investigations is sufficient to draw reasonably definitive conclusions, there are cases where various alternative hypotheses cannot be ruled out. To illustrate this point, and to learn more about the performance of airbags in real-world crashes, as opposed to their performance in federally mandated tests, IIHS has recreated in its crash test facility a NASS case (NHTSA, 1991) from 1991 in which an unbelted driver sustained fatal injuries despite having an airbag.

The case involves the driver of a 1991 Dodge Grand Caravan that ran into the rear of a parked 1958 Chevrolet Bel Air. The unbelted 35-year-old driver of the Grand Caravan sustained fatal injuries to the chest, including a massive crush fracture of the sternum (AIS 2), a contusion of the interventricular septum (AIS 4), and a full-thickness laceration of the anterior wall of the right ventricle with hemopericardium (AIS 5). Using the CRASHPC crash reconstruction program, the NASS investigators concluded that the delta V for the striking vehicle was 74 km/h. The NASS investigators measured a maximum of 29 cm of crush at the front of the Grand Caravan and 126 cm of crush at the rear of the Bel Air. The large amount of total crush indicates that the crash pulse would have been of long duration with an initial relatively low deceleration due to the “soft” rear end of the Bel Air. It was hypothesized by the NASS investigators that the massive chest injuries were likely due to the driver bottoming out the airbag. However, there are other plausible explanations for the observed injuries. The airbag could have deployed late due to the long-duration and initially low-deceleration crash pulse, allowing the driver to move forward and contact the steering wheel before airbag deployment. Or the driver, whose blood alcohol concentration was high (0.16 percent), could have been slumped over the steering wheel when the airbag deployed; this scenario also could explain why the driver ran into the parked car. The objective of this study was to better understand the etiology of the fatal chest injuries in this NASS case.

METHODS

Two vehicle-to-vehicle crash tests were conducted to study the interaction between the driver and the steering wheel/airbag components. Following the crash tests, two static airbag deployment tests were conducted to determine if the airbag alone could have caused the massive chest injuries. The crash tests and static airbag tests were conducted at the IIHS Vehicle Research Center.

Vehicle Crash Tests

A 1991 Dodge Caravan was used as the striking vehicle in the first test (CF00018), and a 1991 Dodge Grand Caravan was used in the second test (CF00019). When these vehicles were weighed prior to the tests, considerable differences were observed when compared with the mass of the Grand Caravan (1,401 kg) in the NASS case. According to VINDICATOR (Highway Loss Data Institute, 2000), a better estimate of the curb mass is 1,666 kg; with the addition of the 73-kg occupant, the total mass of the NASS vehicle increased to 1,739 kg. The test dummy, instrumentation, and onboard cameras increased the striking vehicle mass in the first and second tests by 70 and 133 kg, respectively, above that of the NASS Grand Caravan. Discrepancies also were found between the actual curb mass of the 1958 Chevrolet Bel Air and that reported for the NASS vehicle. The reported mass of the NASS Bel Air (1,596 kg) matches a *Consumer Reports* (Consumers Union, 1958) specification for its shipping weight; the same publication indicated the curb mass (1,667 kg) was within 8 and 77 kg, respectively, of the struck vehicle mass in the first and second tests.

Although the striking vehicles in these tests were different Caravan models, both share the same front structure and safety system (seat belts and airbag) designs. To limit test-to-test variability, the assumption was made that both the striking Grand Caravan and the struck Bel Air in the NASS case were in good structural condition (i.e., the structural members did not contain excessive oxidation). Because it was difficult to obtain more than one 1958 Bel Air in acceptable condition, the struck vehicle in the first test was a 1963 Chevrolet Biscayne. The Biscayne was chosen because of the similarities it shares with the Bel Air including weight, transmission type, and structure (body on X-frame).

Information from the NASS case report was used to help determine the impact velocity, angle, and overlap of the striking vehicle. Prior to each test, the struck vehicle transmission was placed in the “park” position, the steering wheel was straight, and the emergency brake was disengaged. Table 1 summarizes the conditions for each test.

Table 1.
Conditions for Vehicle Crash Tests

	First Test (CF00018)	**Second Test (CF00019)**
Striking Vehicle	1991 Dodge Caravan	1991 Dodge Grand Caravan
Mass (kg)	1,809.0	1,871.5
Target impact velocity (km/h)	56.3	64.4
Front-end overlap (cm)	118.0	124.5
Impact angle (°)	0	0
Struck Vehicle	1963 Chevrolet Biscayne	1958 Chevrolet Bel Air
Mass (kg)	1,659.5	1,744.0
Impact angle (°)	-180	-180

<u>Impact Velocity</u> In the NASS case report, the CRASHPC-calculated delta V for the striking vehicle was 74 km/h. The delta V was recalculated using the corrected mass for each vehicle and an updated crash reconstruction program, SMASH, resulting in a lower delta V of 48 km/h for the Grand Caravan; the Bel Air's delta V was 53 km/h. Using the Bel Air's delta V of 53 km/h and the conservation of momentum principle, an initial estimate of striking vehicle velocity was found to be 102 km/h. Because the majority of the crush in the NASS Bel Air was above the longitudinal frame rails, the delta V estimates were thought to be high. It did not seem reasonable that the crushed Bel Air trunk represented the 273 kJ of dissipated energy estimated by the SMASH program. Consequently, a significantly lower impact velocity (56 km/h) was chosen for the first test. The method used to derive this impact velocity is explained fully in Appendix A. The velocity for the second test was determined by comparing crush measurements from the first test with those reported for the Bel Air in the NASS case.

Impact Overlap and Angle In the reconstruction of the Grand Caravan and Bel Air collision, the NASS investigators assigned principal direction of force values of 5 and -175 degrees to the striking and struck vehicles, respectively. Although this could have been the actual impact angle, the NASS report contains no data to support this finding. Additionally, the field photographs seem to support impact angles of 0 and -180 degrees for each vehicle. To simplify the test configuration and to limit any test-to-test variations from a lateral loading component, a 0-degree impact angle was chosen.

The direct damage measured on the Bel Air by the NASS investigators was 137 cm from its left side, but the field photographs show that the length of direct damage extended from the left side of the vehicle to a point just beyond the C4 measurement location (Figure 1). Because there was no exemplar Bel Air available prior to the first crash test, an approximation was made for this direct damage length. The estimated length of 118 cm was used as the overlap for the first test. When the rear of the Bel Air was measured prior to the second test, the direct damage length was found to be closer to 124.5 cm from the left side of the vehicle.

Figure 1. Photograph of rear-struck 1958 Chevrolet Bel Air from NASS case file (79-021A).

Dummy Selection and Position An instrumented Hybrid III 50th percentile male dummy was positioned in the driver seat of the striking vehicle for each test to represent the 168-cm tall, 72.5-kg driver of the Grand Caravan in the NASS case. Dummy measurements recorded during the tests included head triaxial accelerations, neck shear and axial forces and bending moments, chest triaxial accelerations and deflection, femur and tibia axial forces and bending moments, and biaxial foot accelerations.

For the first test, all dummy seating parameters were set according to the procedures specified in Federal Motor Vehicle Safety Standard (FMVSS) 208 (49 CFR Part 571.208 § 11). For the second test, the seat track, seat back, and dummy position were set according to the University of Michigan Transportation Research Institute (UMTRI) anthropomorphic test device (ATD) positioning procedure for a 50th percentile male (Reed et al., 2001). The UMTRI procedure was used because it places the dummy in a position that is more representative (compared with the current NHTSA procedure) of seat positions chosen by male drivers who are the same size as the 50th percentile male ATD. The UMTRI position placed the dummy's H-point 60 mm aft of the FMVSS 208-prescribed position used in the first test. The UMTRI position also resulted in a chest-to-steering-wheel-hub minimum distance that was 49 mm greater than that achieved in the first test. Following final positioning, measurements from various parts of the dummy to a number of vehicle interior points were made. These measurements are described in Appendices B and C.

Static Airbag Deployment Tests

Two static airbag deployment tests were conducted in a 1991 Dodge Grand Caravan with a Hybrid III 50th percentile dummy positioned over the airbag. In the first airbag test (KA00001), the dummy was positioned in the driver seat, then the upper torso was rotated fully forward. This setup was used to represent how the NASS driver might have been positioned if he was slumped over the steering wheel. The goal of the second airbag test (KA00002) was to fully expose the chest to the airbag deployment force by placing it as close to the airbag module as possible. Previous research has shown that the highest dummy injury values are produced when the chest is placed directly on the airbag module (Horsch et al., 1990; Melvin et al., 1993). The second airbag test was considered the worst-case airbag loading scenario for the NASS driver.

After the dummy was positioned in each test, the airbag was manually deployed. High-speed (500 frames/sec) video and dummy head, neck, and chest instrumentation data were collected during the tests. Figures 2 and 3 show the dummy's position with respect to the airbag module in these tests. Table 2 summarizes the dummy clearance measurement in each test.

Figure 2. In the first test (KA00001), the dummy was seated in a normal position, and the upper body was pushed forward.

Figure 3. In the second test (KA00002), the dummy was pushed forward in the seat until the chest was directly on the airbag module.

Table 2.
Dummy Clearance Measurements for Static Airbag Tests

Measurement	**First Test (KA00001)**	**Second Test (KA00002)**
Head to rim (mm)	19	–
Bottom of nose to rim (mm)	–	35
Rim to abdomen (mm)	50	0
Hub to chest, minimum (mm)	50	0
Striker to H-point, horizontal (mm)	273	357
Striker to H-point, vertical (mm)	38	18

RESULTS

Vehicle Crash Tests

<u>**Vehicle Response and Crush Measures**</u> Vehicle crush profiles for the 1991 Caravan and 1958 Bel Air are shown in Figures 4 and 5. In the first test (CF00018), the actual impact velocity was 57.6 km/h, and the longitudinal delta V for the Caravan was 30.8 km/h. The crush profile of the Caravan in this test was similar in shape to that of the NASS Grand Caravan, but its extent (particularly on the right side) was significantly less. Similarly, the rear-end crush of the 1963 Biscayne was less than that of the NASS Bel Air.

In the second test (CF00019), impact velocity was increased to 64.4 km/h in an attempt to increase the resultant crush in both vehicles. This velocity was chosen because it was believed that only a minor increase in impact velocity was necessary to produce the crush observed in the NASS case. Velocity measures initially were calculated in English units—i.e., the 8-km/h increase between tests actually corresponds to a change in target impact velocity from 35 to 40 mi/h.

The actual impact velocity (64.0 km/h) for the second test resulted in an increased delta V of 37.1 km/h. Unexpectedly, the Grand Caravan crush pattern in this test was much different than that observed in both the first test and the NASS case. Figure 6 shows that although the crush on the right side of the Grand Caravan increased from the Caravan, it was approximately 10 cm less than the NASS Grand Caravan, and the maximum crush location was shifted from the far right side to the center of the vehicle. The postcrash contour of the Bel Air in the second test shows that its rear structure sustained approximately 50 cm less crush than the NASS Bel Air (Figure 5). This damage differed from the NASS Bel Air in that override of the rear frame rails was not observed (Figure 8). Postcrash views of the Grand Caravan and Bel Air used in the second test are shown in Figures 7 and 8. Figure 9 shows the NASS Bel Air for comparison purposes.

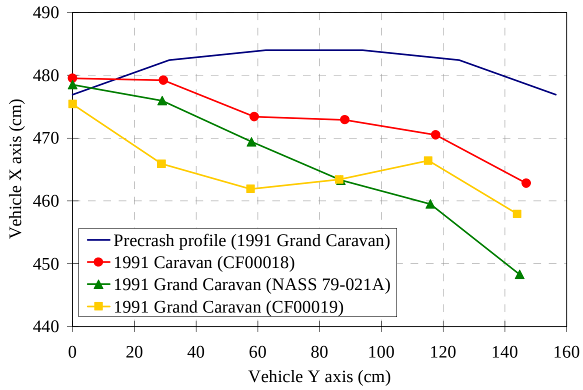

Figure 4. Overhead crush profile. Horizontal axis represents overhead view of vehicle Y axis, where 0 cm and 160 cm represent the left and right sides of the vehicle, respectively.

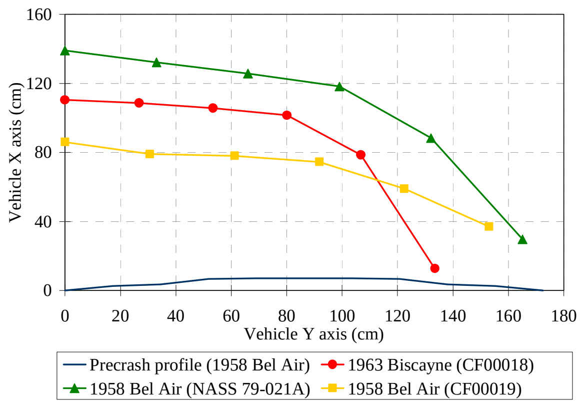

Figure 5. Struck vehicle crush profiles measured at rear bumper. Horizontal axis represents overhead view of vehicle Y axis, where 0 cm and 180 cm represent the left and right sides of the vehicle, respectively.

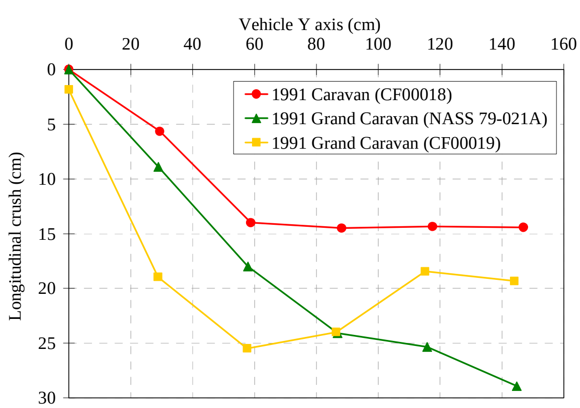

Figure 6. Overhead crush extent. Longitudinal vehicle crush is measured in relation to its undeformed position.

Figure 7. Postcrash view of 1991 Dodge Grand Caravan used in second crash test (CF00019)

Figure 8. Postcrash view of 1958 Chevrolet Bel Air used in second crash test (CF00019).

Figure 9. Photograph of rear-struck 1958 Chevrolet Bel Air from NASS case file (79-021A).

Dummy Kinematics Analysis of the high-speed film taken from onboard cameras showed that airbag deployment in both tests occurred at approximately the same time (28-30 ms into the crash). In both tests, the airbag made contact with the chest prior to full inflation, causing minor increases in chest sternum displacement and acceleration. The dummy then traveled forward into the deploying airbag, where the chest began to load the bottom of the airbag. As forward travel continued, the dummy's face began to load the airbag, and the steering column started to tilt upward. Upward movement of the steering column caused the bottom of the rim to move up toward the chest, and as the dummy continued to move forward, contact between the lower rim and the dummy's chest occurred. Figure 10 shows the contact between the shifted steering column and the dummy's chest in the second test. Contact with the steering wheel rim occurred at 140 ms in the first test and at 110 ms in the second test. After contacting the rim, the dummy moved forward and slightly upward before rebounding back into the seat. Table 3 summarizes the timing of the airbag deployment and dummy contacts in each test.

Figure 10. Dummy chest-to-steering wheel contact observed in the first crash test (CF00018). Similar steering wheel movement and chest contact was observed in the second crash test (CF00019).

Table 3.
Timing of Airbag Deployment and Dummy Contacts for Vehicle Crash Tests

Event	**First Crash Test (CF00018)**	**Second Crash Test (CF00019)**
Deployment of airbag (ms)	28	30
Chest contact during deployment (ms)	36	38
Airbag fully deployed (ms)	54	54
Chest contacts steering wheel rim (ms)	140	110

Dummy Injury Measures The only measure that indicated a significant injury risk was chest sternum displacement. Head, neck, and lower extremity injury measures were all well below any published injury assessment reference value (IARV) for a 50th percentile male.

In both tests, chest sternum displacement exceeded the 50-mm IARV when the chest was in contact with the steering wheel rim. Investigation of the thorax following the tests showed that several of the rib modules were permanently deformed from off-axis loading to the chest. Because there was an off-axis loading component, it is likely that injury measures based on chest deflection underestimate chest injury risk.

Table 4 summarizes the dummy injury measures for the vehicle crash tests. Figures 11-13 show the time curves for dummy chest A-P and resultant accelerations and chest sternum displacement.

Table 4.
Dummy Injury Measures and Vehicle Dynamics for Vehicle Crash Tests

		IARV	**First Crash Test (CF00018)**	**Second Crash Test (CF00019)**
Head	Resultant acceleration (g)	80	20	18
	HIC-15	700	23	19
Neck	A-P shear force (kN)	±3.1	-0.3	-0.3
	Axial compression (kN)	4.0	0.0	0.1
	Axial tension (kN)	3.3	0.6	0.7
	Flexion moment (Nm)	310	22	31
	Extension moment (Nm)	122	7	7
Chest	Resultant acceleration (3 ms clip, g)	60	16	19
	Sternum displacement (mm)	-50	**-51**	**-52**
	Viscous criterion (m/s)	1.0	0.4	0.4
	Sternum deflection rate (m/s)	-8.2	-2.1	-1.6
Vehicle	Actual Impact speed (km/h)		57.6	64.0
	Resultant acceleration (g)		16	15
	Longitudinal acceleration (g)		9	-11
	Lateral acceleration (g)		2	-2
	Vertical acceleration (g)		-13	-13

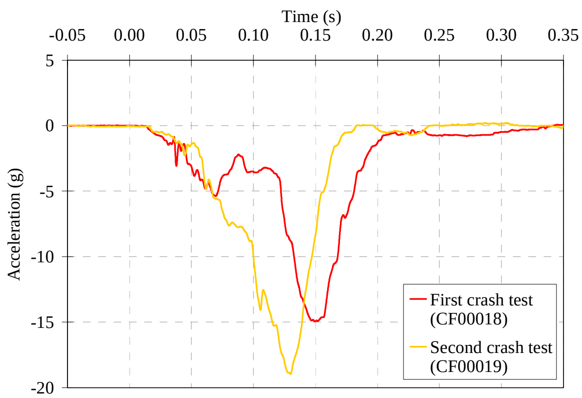

Figure 11. Dummy chest A-P accelerations recorded during first (CF00018) and second (CF00019) crash tests.

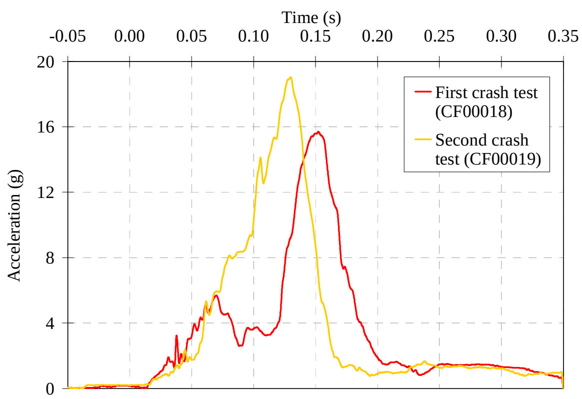

Figure 12. Dummy chest resultant accelerations recorded during first (CF00018) and second (CF00019) crash tests.

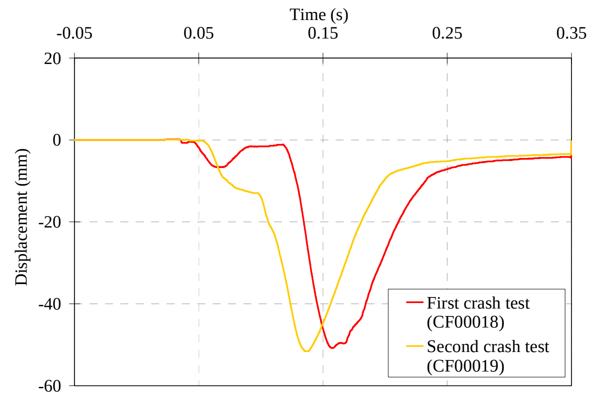

Figure 13. Dummy chest sternum displacements recorded during first (CF00018) and second (CF00019) crash tests.

Static Airbag Deployment Tests

Dummy Injury Measures For both test configurations, dummy injury measures showed that there was no serious risk of head or neck injury from the airbag alone. Chest injury measures for the "slumped" dummy position used in the first test did not exceed any of the IARVs, but the chest-on-module position used in the second test resulted in injury measures that exceeded the IARV for chest viscous criterion and approached IARVs for sternum displacement and deflection rate. Table 5 summarizes the dummy injury measures for the static airbag tests.

Table 5.
Dummy Injury Measures for Static Airbag Tests

		IARV	Static Airbag Test (KA00001)	Static Airbag Test (KA00002)
Head	Resultant acceleration (g)	80	29	28
	HIC-15	700	51	45
Neck	A-P shear force (kN)	±3.1	-1.6	-1.5
	Axial compression (kN)	4.0	0.2	0.1
	Axial tension (kN)	3.3	2.2	1.8
	Flexion moment (Nm)	310	2	7
	Extension moment (Nm)	122	78	45
Chest	Resultant acceleration (3 ms clip, g)	60	15	40
	Sternum displacement (mm)	-50	-38	-48
	Viscous criterion (m/s)	1.0	0.5	**1.8**
	Sternum deflection rate (m/s)	-8.2	-2.9	-7.2

DISCUSSION

The purpose of the first crash test was to help determine a crush-based impact speed for the second crash test, which was to be an accurate re-creation of the NASS case. Although the impact velocity for the second test was increased, the resulting crush extent and shape differed from that observed in the NASS case. In the second test, the maximum crush of the striking vehicle occurred close to the vehicle longitudinal centerline, as opposed to the crush of the NASS vehicle that increased steadily toward the right side

(Figure 6). Decreasing the impact overlap might have directed a greater portion of the load path toward the right side of the Grand Caravan, thereby increasing the likelihood of a NASS-like triangular crush profile (Figure 4) and greater maximum crush.

A retrospective analysis comparing the SMASH and actual delta Vs showed only 8 and 3 km/h differences for the first and second crash tests, respectively. Because these differences were smaller than originally expected, the SMASH delta V for the NASS case was used to determine a rough estimate of the actual striking vehicle velocity. This exercise was conducted primarily so that a comparison could be made between the second crash test and the NASS case. The SMASH-estimated striking vehicle velocity (v_{SMASH}) was calculated for the two crash tests and the NASS case from the following conservation of momentum-based equation:

$$v_{\text{SMASH}} = \frac{(m_1 + m_2)}{m_1} \Delta v_2 \, ,$$

where

m_1, m_2 = striking and struck vehicle masses, respectively

Δv_2 = SMASH-calculated delta V for the struck vehicle.

The SMASH-estimated velocities for the first and second crash tests and the NASS case were 77.1, 68.4, and 95.7 km/h, respectively. The actual impact velocities (v_{actual}) from the two crash tests were used to determine the SMASH-to-actual velocity ratio ($v_{\text{SMASH}}/v_{\text{actual}}$). These ratios ranged from 1.34 for the first test to 1.07 for the second test. Using this ratio, an approximation of the NASS striking vehicle velocity is in the range of 71.4 to 89.6 km/h, or 7.4 to 25.6 km/h faster than the NASS "re-creation" test. Increasing velocity alone could have increased the total crush in both vehicles, but it would not have influenced the disparity in crush profile.

In addition to velocity and overlap, differences in rear-end heights of the Bel Airs in the second crash test and the NASS case could have been a factor in the crush dissimilarities. Such differences could have resulted from changes (or wear) to the rear tires and suspension. Extreme changes in either could have caused the Grand Caravan to override the Bel Air in the NASS case (Figure 1), resulting in a load path that no longer was dependent on the Bel Air's longitudinal frame rails. The override load path most likely would have been less stiff, thereby changing the overall vehicle response.

Although there were differences in crush, it is not clear whether the source of the chest injuries would have changed had the crash test configuration been altered. As mentioned above, decreases in impact overlap (and possible velocity increases) would be required for the experimental crush measures to match those of the NASS case. Depending on which adjustment is made, the end effect on vehicle response could either be a decrease in vehicle acceleration (as overlap is decreased) or an increase in both delta V and acceleration (as impact velocity in increased). A decrease in vehicle longitudinal acceleration would expectedly result in dummy-airbag interactions similar to the first crash test. Increases in longitudinal acceleration would likely cause the airbag to deploy at the same time as (or slightly earlier than) the airbags in the striking vehicles in this study. If the airbag in the NASS vehicle deployed much earlier than the airbags in this study (~30 ms into the crash)—unlikely, because earlier airbag firings are not usual in crashes with initial low deceleration—it is possible that the airbag could have lost most of its volume and pressure before the occupant began loading it, thereby making it easier for bottoming out to occur; this would confirm the original NASS hypothesis. However, this hypothesis is weakened by analysis of the high-speed film taken during the crash tests that shows sufficient airbag volume when the dummy contacted the steering wheel. In both tests, steering column movement, not low airbag pressure or volume, caused the chest contact with the lower rim.

The chest injuries that resulted from contact with the lower steering wheel rim were observed in both crash tests conducted at two different impact velocities. The deflection-based chest injuries observed in these tests, which were underestimated due to off-axis loading, correspond to a 40-50 percent risk of an AIS 3+ thoracic injury (Mertz et al., 1991). These injuries had minimal dependence on airbag timing because the tilting of the steering wheel rim produced a situation in which the airbag was not in an optimum position to protect the occupant. In a previous study, Yoganandan et al. (1993) conducted sled tests in which an unbelted occupant's forward motion was restrained by a knee bolster and an airbag; these restraint conditions were similar to the ones employed in the current study. In the sled tests, thoracic contact with the lower steering wheel rim that was observed produced primarily lower rib fractures (AIS 2-4) in the human cadaveric subjects. Although there were no observed fractures to the sternum in these tests, several did occur to the 4th and 5th thoracic ribs. These ribs are vertically aligned with the bottom of the heart, which means that the rim loading could have been the injury-causing mechanism in the NASS case.

Results of the static airbag tests show that when the dummy was in the slumped position, there was very minor risk of injury from the airbag alone. In the second airbag test, the chest-on-module position produced higher chest injury measures, including a maximum viscous criterion (1.8 m/s) that exceeded the 1.0 m/s IARV, which corresponds approximately to an 85 percent risk of a serious (AIS 4+) thoracic injury (Viano and Lau, 1986). These results were republished in a Horsch et al. (1990) study (of which Viano and Lau were co-authors) showing a 100 percent risk of AIS 4+ injuries at this viscous criterion level. Using swine as physiologic surrogates, Horsch et al. observed severe (AIS 3-5) heart lacerations and contusions in static airbag deployment tests that produced viscous criterion values greater than 1.0 m/s in a Hybrid III 50th percentile male dummy. Horsch et al. also showed a similarity between Hybrid III viscous criterion responses in frontal sled tests and static airbag tests, which suggests that an out-of-position dummy in the re-creation of the NASS case would have produced peak viscous criterion measures similar to those observed in the static airbag tests. A further deduction can be made that the NASS injuries could have resulted from direct loading to the chest.

Schroeder and Eidam (1997) conducted static airbag deployment tests with cadavers that resulted in fractures to the sternum and ribs when subjects were positioned within 0-50 mm of the airbag module. The airbag-induced injuries to the skeletal structure in these tests match up very well with the results observed in both the NASS case and the static airbag tests conducted for this study. Results of the Schroeder and Eidam study provide further proof that the chest injuries in the NASS case could have been sustained directly from airbag deployment.

CONCLUSIONS

In this study, two vehicle-to-vehicle crash tests and two static airbag deployment tests were conducted to better understand the mechanisms that led to fatal chest injuries in a 1991 NASS case. In both crash tests, the dummy sustained significant loading from the steering wheel that indicated a serious risk of thoracic injury. The steering wheel loading did not result from bottoming out the airbag. Instead, the injury risk resulted from the upward rotation of the steering wheel rim, which also caused the airbag to move upward and out of a position where it could have protected the chest. The static airbag test results indicated that the airbag could have produced punch-out forces high enough to produce severe thoracic injuries.

Even though the crash test did not exactly re-create the NASS case, the dummy-steering wheel interactions observed in both tests are significant. The injuries in the NASS case ranged from AIS 2 to AIS 5. If a third crash test with conditions that would be even closer to the real-world scenario (i.e., increasing impact velocity and decreasing overlap) had been possible, the increased delta V likely would result in even higher injury risk being recorded; however, there is no reason to expect that the injury mechanism—contact with the rotated steering wheel rim—itself would change.

Results from this study demonstrate that two different mechanisms could have caused the massive chest injuries in the NASS case. Either the occupant was out of position and the airbag deployment forces caused his fatal injuries, or the steering wheel had rotated upward so that the airbag was not in a position to prevent the fatal injuries caused by contact with the steering wheel rim. The test results refute the bottoming-out hypothesis proposed by the NASS investigators.

This attempt to re-create a frontal crash in which an unbelted occupant sustained fatal injuries despite an airbag illustrates the caution necessary when trying to determine injury causation in real-world crashes. Although NASS cases are investigated in detail, significant errors in the crash reconstructions are common; for example, NASS estimates of delta V often are significantly in error. In this case, the NASS estimate of delta V for the Grand Caravan was 74 km/h; however, using the correct mass information and an updated crash reconstruction program produced the much lower estimate of 48 km/h. Similarly, NASS investigators' attributions of injury causation need to be treated with caution. As this case illustrates, if an airbag fails to protect in a crash in which it could be expected to, there can be many possibilities: the airbag had insufficient power and was bottomed out, the airbag inflation forces caused the injury, or the airbag was not in a position to protect because of steering wheel rotation. This latter possibility has not received sufficient attention to date, perhaps because in full-width barrier crash tests steering wheel movement typically is minimal. However, in offset and other frontal crash configurations, steering wheel rotation and rearward movement is much more likely (Zuby and O'Neill, 2001), and all such movement can compromise the ability of an airbag to provide effective protection.

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APPENDIX A

Impact Velocity Calculation for First Crash Test

The striking vehicle impact velocity for the first crash test was derived using conservation of energy and momentum equations. In order to determine the impact velocity required that would produce a crush extent similar to the NASS collision, the conservation of energy principles were applied to a hypothetical frontal offset crash involving two Grand Caravans; mass (1,739 kg), crush, and dissipated energy (E_D) for each vehicle are identical. Applying the conservation of energy:

$$E_1 + E_2 = E_F + 2E_D\,, \qquad (1)$$

where

E_i = initial kinetic energy of vehicle i , $E_1 = ½\, m v_1^2$ and $E_2 = 0$

$E_F = ½(m_1 + m_2)v_F^2$, the kinetic energy of system (both vehicles) when $v_1 = v_2$

E_D = 51,521 J, the dissipated energy from the initial CRASHPC reconstruction. Equation 1 uses $2E_D$ because it is accounting for the crush energy of two vehicles.

By assuming a simplified collision in which momentum is conserved,

$$v_F = (m_1 v_1) / (m_1 + m_2) = ½\, v_1 \qquad (2)$$

Substituting Equation 2 into Equation 1 allows for the isolation of the initial impact velocity, v_1 (m/s).

$$v_1 = 15.4 \text{ m/s} = 55.4 \text{ km/h}$$

Because these calculations were initially performed in English units the impact velocity was rounded up from 34.4 to 35 mi/h (56.3 km/h).

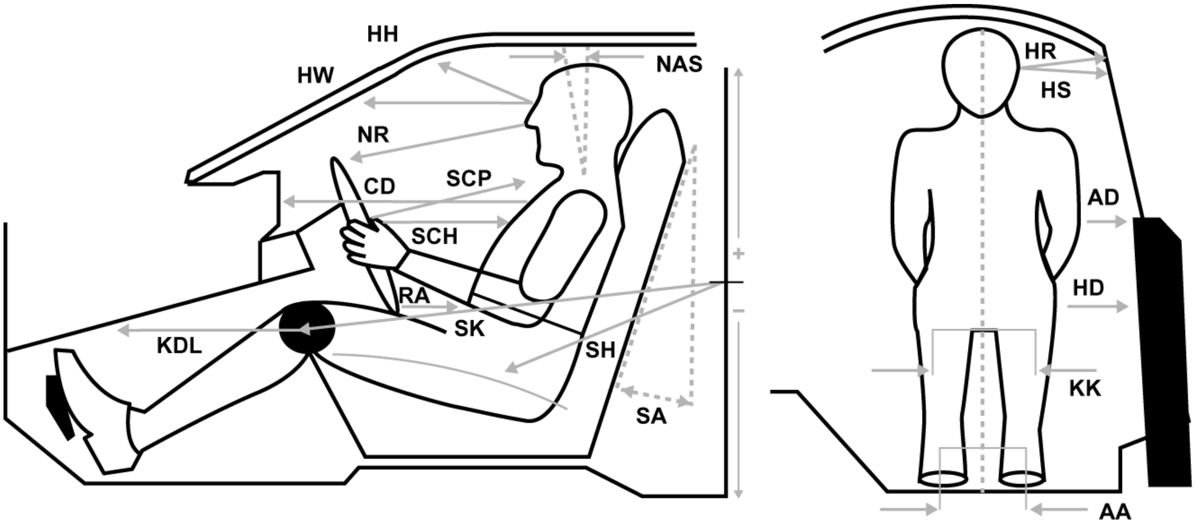
APPENDIX B

Dummy Clearance Measurements for First Crash Test

Test number:	CF00018
Vehicle make/model:	Dodge Caravan
Vehicle model year:	1991
Seat type:	Manually adjusted bucket seat (fore/aft) with fixed seat back
Test Position	
Seat back information:	Fixed
Seat cushion:	Set to 6th of 11 notches from forward-most position
Steering column adjustment:	Set to midpoint of tilt range

Location	**Code**	**Measure**	**Location**	**Code**	**Measure**
Head to header	HH	444	Neck angle, torso 90	NAT90	–
Head to windshield	HW	665	Neck angle, seated	NAS	5.2
Nose to rim	NR	461	Torso angle (NAT90 – NAS)	TA	–
Chest to dash	CD	578	Striker to knee*	SK	610
Rim to abdomen	RA	154	Striker to knee angle*	SKA	-4.0
Knee to dash, left	KDL	249	Striker to H-point, horizontal	SHH	209
Knee to dash, right	KDR	249	Striker to H-point, vertical	SHV	-36
Steering wheel to chest, horizontal	SCH	287	Ankle to ankle	AA	320
Steering wheel to chest, perpendicular	SCP	406	Knee to knee	KK	330
Steering wheel to chest, reference	SCR	381	Arm to door	AD	80
Hub to chest, minimum	HCM	216	H-point to door	HD	141
Pelvic angle	PA	25.0	Head to A-pillar	HA	560
Seat back angle	SA	fixed	Head to roof	HR	217
			Head to side window	HS	246

All distance measurements are in millimeters (mm).
* These measurements were made in a vertical plane containing the striker and parallel to the driver door sill.



APPENDIX C

Dummy Clearance Measurements for Second Crash Test

Test number:	CF00019
Vehicle make/model:	Dodge Grand Caravan
Vehicle model year:	1991
Seat type:	Electrically adjusted bucket seat (fore/aft and seat back angle)
Test Position	
Seat back information:	Adjusted to accommodated dummy torso recline position of 10°
Seat cushion:	1.2 cm from rear track position
Steering column adjustment:	Set to midpoint of tilt range

Location	**Code**	**Measure**	**Location**	**Code**	**Measure**
Head to header	HH	505	Neck angle, torso 90	NAT90	20.0°
Head to windshield	HW	750	Neck angle, seated	NAS	3.7°
Nose to rim	NR	475	Torso angle (NAT90 – NAS)	TA	16.3°
Chest to dash	CD	615	Striker to knee*	SK	560
Rim to abdomen	RA	211	Striker to knee angle*	SKA	4.6°
Knee to dash, left	KDL	310	Striker to H-point, horizontal	SHH	149
Knee to dash, right	KDR	309	Striker to H-point, vertical	SHV	-38
Steering wheel to chest, horizontal	SCH	341	Ankle to ankle	AA	330
Steering wheel to chest, perpendicular	SCP	439	Knee to knee	KK	305
Steering wheel to chest, reference	SCR	418	Arm to door	AD	80
Hub to chest, minimum	HCM	265	H-point to door	HD	145
Pelvic angle	PA	24.8°	Head to A-pillar	HA	608
Seat back angle	SA	-	Head to roof	HR	240
H-point to head CG angle		10°	Head to side window	HS	261

All distance measurements are in millimeters (mm).

* These measurements were made in a vertical plane containing the striker and parallel to the driver door sill.